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THERMAL PROPERTIES OF CONCRETES INCORPORATING FLY ASH OR SILICA FUME

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THERMAL PROPERTIES OF CONCRETES INCORPORATING FLY ASH OR SILICA FUME

by

V. Sivasundaram[1]

ABSTRACT

This paper presents the results of an investigation in which the thermal conductivity, specific heat, and thermal diffusivity of concretes incorporating fly ash or silica fume were measured. High-volume fly ash concretes consisting of 100, 150 and 180 kg/m^3 of Type I cement and ASTM Class F fly ash at 58% of cementitious materials were tested. These concretes incorporated crushed limestone and granitic gravel as coarse aggregates. Normal strength silica fume concretes (28-day strength ≈ 27 MPa) with 5, 10, and 15% silica fume replacing cement, and a high-strengtn silica fume concrete (28-day strength ≈ 84 MPa) containing 8% silica fume were also tested for thermal properties. Crushed limestone was used as coarse aggregate in the silica fume concretes.

Thermal conductivity and thermal diffusivity measurements were made using the transient thermal probe method (EPRI EL - 2128) and the Shannon and Wells technique, respectively. These parameters were determined at five different moisture levels ranging from fully saturated to completely dry. The specific heat of dry material chipped from each concrete specimen was determined with a calorimeter.

The test results showed that there were no significant differences between the thermal properties of concretes with crushed limestone and granitic gravelstone aggregates. Among the high-volume fly ash concretes tested, the concrete with 155 kg/m^3 of cement appeared to have the optimum characteristics, yielding lower thermal conductivity and thermal diffusivity values

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together with reasonably high 28-day compressive strength of about 36 MPa. The thermal conductivity and thermal diffusivity values of the high-strength silica fume concrete were higher than those of the other concretes at all moisture levels. The 28-day compressive strength of this concrete was 84 MPa. The normal strength silica fume concretes with 5, 10, and 15% silica fume gave low values for thermal properties and had 28-day strengths of about 28 MPa. There were no significant differences observed in the specific heat values of the concretes, which were determined in the dry condition.

Keywords: Thermal conductivity, thermal diffusivity, specific heat, fly ash, silica fume, high-volume fly ash concrete, high-strength concrete, transient thermal probe method, moisture content, air entrainment.

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INTRODUCTION

The thermal properties of concrete are given prime consideration in the design of structures such as dams, where thermal and volume stability are important, and in lightweight concrete structures where the insulating value of the concrete is a major factor. This paper reports on an investigation made to determine the thermal properties of concretes incorporating supplementary cementing materials such as fly ash or silica fume. The thermal properties studied in this investigation are thermal conductivity, thermal diffusivity, and specific heat.

Thermal conductivity is a measure of the ability of the material to conduct heat and may be defined as the ratio of the rate of heat flow to the temperature gradient (1). One type of dimension used for thermal conductivity is watts per degree celsius-metre (W/°C-m.). The thermal conductivity of a concrete depends on variables such as concrete composition, mineralogical character of the aggregates, moisture content, density, and temperature. Moisture content of the concrete is an important parameter affecting thermal conductivity, because it varies directly with moisture content. Also, the conductivity may increase appreciably when a concrete with sufficient moisture is subjected to freezing.

The specific heat is defined as the ratio of the amount of heat required to raise a unit weight of material 1 degree to the amount of heat required to raise the same weight of water 1 degree(1). In the system of units where the heat capacity of the water is 1.0 cal/g.°C, the specific heat values are the same. The specific heat of concrete is not much affected by the mineralogical differences of aggregates; however, it varies directly with concrete temperatures.

Thermal conductivity governs the rate of heat flow into, through, or out of a concrete structure. Thermal diffusivity, on the other hand, is a measure of the ease or difficulty with which the concrete undergoes temperature change as a result of heat loss or gain, and is defined numerically as thermal conductivity divided by the product of specific heat and density. Hence, thermal diffusivity values are affected by the variables and conditions influencing thermal conductivity, specific heat, and density. Since the above properties are sensitive to the moisture content of the concrete, the thermal diffusivity values should be based on conductivities and densities corresponding to the condition of the concrete in service.

The thermal properties of concrete influence the dissipation of internal heat in massive structures as well as the damping of ambient cyclic variations. The favourable thermal insulation characteristics of normal weight concrete and the high insulation characteristics of lightweight concrete have been effectively used in construction, where resistance to steady-state heat flow is needed. Normal weight concrete ideally combines strength and durability with a favourable thermal diffusivity property which is most effective in reducing the heating and cooling requirements of a building's interior (1).

Although a good deal of information has been published on thermal properties of concretes containing various aggregates, the data on concretes incorporating supplementary cementing materials are scarce. The present investigation was undertaken to initiate a data base on the thermal properties of the above concretes.

SCOPE

The thermal properties were measured on ten different types of concrete incorporating fly ash or silica fume. Crushed limestone and granitic gravelstone were used as coarse aggregates in the concretes. The concretes were mixed in the CANMET laboratory and the specimens were subjected to thermal properties measurements after 28 days of moist curing. The measurements were made at five different moisture levels of the specimens, ranging from fully saturated to completely dry conditions. The specific heat measurements of the concretes were made in dry conditions. Compressive strengths were determined at the ages of 7 and 28 days.

MATERIALS

Cement - Normal portland cement, ASTM Type I was used. Its physical properties and chemical analysis are given in Table 1.

Fly Ash - ASTM Class F fly ash (low-calcium) obtained from Nova Scotia was used. The Physical properties and chemical analysis of the fly ash are given in Table 1.

Silica fume - Silica fume from a Canadian source was used. The physical properties and chemical analysis of the fume are given in Table 1.

Aggregates - Two types of coarse aggregate were used: crushed limestone and crushed granitic gravel, both with a maximum size of 19mm. The fine fraction was natural sand. The grading and physical properties of the coarse and fine aggregates are given in Tables 2 and 3.

Superplasticizer - A sulphonated naphthalene formaldehyde condensate of Japanese origin was used. This superplasticizer is available as a dark brown 42% solids aqueous solution, with a density of 1200 kg/m^3.

Air-entraining admixture - Two types of air-entraining admixtures, a sulphonated hydrocarbon and a synthetic resin, were used.

CONCRETE MIXTURES

Six high-volume fly ash concretes were made with cement contents of 100, 150, and 180 kg/m^3 of portland cement. The proportion of fly ash in the total cementitious materials was kept at 58% in each of them. Crushed limestone was used as coarse aggregate in one series, and crushed granitic gravel as the coarse aggregate in another series. In addition, three silica fume concretes were made with silica fume at 5, 10, and 15 percent of cementitious material content. In this instance, only crushed limestone was used as coarse aggregate, and the total cementitious material content was kept at 275 kg/m^3. The tenth concrete mixture was a high-strength silica fume concrete with silica fume at 8% of the total cementitious materials. The coarse aggregate used in this concrete was crushed limestone. The proportioning of the concrete mixtures is summarized in Table 4.

For all mixtures, the graded coarse and fine aggregates were weighed in dry condition. The coarse aggregate was then immersed in water for 24 hours, the excess water was decanted, and the water retained by the aggregate was determined by weight difference. A predetermined amount of water was added to the fine aggregate, which was then allowed to stand for 24 hours. The 0.03 m^3 concrete mixtures were mixed in a laboratory counter-current mixer and nine 103 x 205-mm cylinders were cast from each. Also, three cylinders from each concrete mixture were cast with a 10-in. long metal probe inserted right to the bottom of the mold. The properties of freshly-mixed concrete, i.e., temperature, slump, unit weight, and air content are given in Table 5.

CURING AND TESTING OF SPECIMENS

After casting, all the moulded cylinders were covered with water-saturated burlap, and left in the casting room at 23 ± 1.7°C and 50% relative humidity. After 24 hours, the cylinders were demoulded, weighed and transferred to the moist-curing room until testing. Three cylinders from each concrete were tested in compression at 7 and 28 days. After 28 days of moist-curing, the cylinders with the cast-in-place metal probes were subjected to thermal testing.

The transient thermal probe method (EPRI EL-2128) was used to determine the thermal conductivity, and the Shannon and Wells technique (ASTM Proc. Vol. 47, p 1044) was used to determine thermal diffusivity. A paper describing these procedures and their theoretical bases is given in Appendix A. These procedures were developed originally to determine the thermal properties of soil, but were adapted for concrete thermal property measurements. The values of thermal conductivity and thermal diffusivity of the concrete specimens were measured at 5 different moisture levels ranging from fully saturated to completely dry, by oven drying the specimen in stages. At each stage the specimens were wrapped in plastic and allowed to come to moisture and temperature equilibrium prior to the thermal testing. The specific heat of dry material chipped from each concrete specimen was determined using a calorimeter.

Thermal testing was carried out using the GEOTHERM TPA-5000, a system that fully automates the transient thermal probe test. It is micro-computer controlled and provides programmable power to thermal probes, reads temperature sensors, probe current and voltage, and computes the thermal conductivity progressively during the test. The unit consists of a programmable 10-amp, 60-volt power supply, a 10-channel data

acquisition system and an HP-85B micro-computer. A nominal 110 volt power source is required. Various built-in error reducing features ensure that the test complies with the theoretical assumptions of the line heat source theory. A statistical analysis of data indicates whether an acceptable test has been accomplished. Test data (time, temperature, power) are printed, plotted and stored on tape so that future analysis and reference to the results may be made.

RESULTS AND DISCUSSION

The thermal conductivity and thermal diffusivity values of the concretes measured at various levels of moisture content from fully saturated to oven-dry condition are shown in Table 6. The specific heat values were measured at oven-dry condition only. The thermal conductivity and thermal diffusivity values versus moisture content have been plotted in Fig. 1 through 10, and Fig. 11 and 12 show all the thermal dry-out curves on one plot.

In all the concretes tested, the thermal conductivity is seen to increase with moisture content until saturation. The thermal diffusivity, in general, appears to reach a peak before saturation. In the case of silica fume concretes, the high-strength concrete containing 489 kg/m^3 of cement and 8% silica fume (No. 10) exhibits the highest thermal conductivity and thermal diffusivity values from dry condition to the saturated condition. This concrete is rich in cementitious materials and has an impervious system with a high density; moreover, in this system there is no entrained air, which usually acts as an insulator and reduces the thermal conductivity. These factors appear to have contributed to the high values of thermal properties of this concrete. All the other concretes were air-entrained.

In the high-volume fly ash concretes made with both crushed limestone (No. 1, 2, 3) and granitic gravel (No. 4, 5, 6), the thermal properties appear to be at the same level in dry condition, although the thermal conductivity and thermal diffusivity of concretes No. 2 and 5 appear to be slightly higher than that of the others. The low levels of entrained air and the greater density of these concretes might have contributed to this effect. No significant differences were observed among the thermal properties of concretes made with limestone and granitic gravelstone aggregates. However, it was noted that in both concretes No. 1 and 4 (with 100 kg/m^3 of cement and 135 kg/m^3 of fly ash), the increase in thermal conductivity and thermal diffusivity values were relatively high from dry condition to saturated condition. The higher proportion of aggregates in these two concretes compared to that of the other concretes could have been a contributing factor. In the case of the fly ash concretes with 180 kg/m^3 of cement (concrete No. 3 and 6), the increase in mixing water, the reduction in total aggregate content and the lower densities appear to cause the low values of thermal properties.

The thermal properties of normal strength silica fume concretes (No. 7, 8, and 9 with 5, 10, and 15% silica fume, respectively) were the lowest in the dry condition, and the increase from dry condition to the saturated condition was not very high for these concretes. These concretes were proportioned with high water content and had the lowest densities overall within the concretes tested. These factors could have contributed to the low values of thermal properties in the concretes.

Table 7 shows some typical values reported for thermal conductivity of concretes incorporating different aggregates. The thermal conductivity at varying moisture levels are given in the table. The thermal properties of concretes used in certain

dams built in the United States are shown in Table 8. The properties given in Table 8 were measured at higher temperatures, whereas the values in Table 7 were measured at normal ambient temperatures. The properties measured in the present investigation are seen to fall in the same range.

The compressive strengths of concretes measured at ages of 7 and 28 days are given in Table 5. The silica fume concretes No. 7, 8, and 9 had strengths ranging from 24 to 29 MPa at 28 days, which were not very high, thus offsetting the advantage of low thermal properties. The high-strength concrete (No. 10) reached a strength of 84.2 MPa at 28 days. Among the concretes investigated, the high-volume fly ash concrete with 150 kg/m^3 of cement (No. 2 and 5) appears to give reasonably high strength of about 35 MPa together with low values of thermal properties.

In the high-volume fly ash concrete system, the quantity of mixing water in the concrete appears to be more critical than the water-to-cementitious materials ratio. In concretes No. 3 and 6, the total cementitious material content was 430 kg/m^3, and the water-to-cementitious materials ratio of 0.31 was the same as that of concretes No. 2 and 5 with 360 kg/m^3 of cementitious material. However, in spite of the increased cementitious material, the compressive strengths of concretes No. 3 and 6 were lower than that of concretes No. 2 and 5. It appears that the increase in water content causes a reduction in strength regardless of the water-to-cementitious materials ratio. Further research is needed in this area. In the case of concretes No. 1 and 4, the very low quantity of cementitious material caused the lower strengths.

The specific heat values were calculated for concretes in the dry condition only. The values ranged from 0.164 to 0.172 cal/g.°C for the concretes tested, and as such were not significantly different.

CONCLUSIONS

Among the ten different concretes investigated, no significant differences in thermal properties were noted between the concretes incorporating crushed limestone and granitic gravelstone aggregate. The high-strength, non-air entrained concrete incorporating 489 kg/m^3 of cement and 8% silica fume (compressive strength ≈ 84 MPa) gave the highest values of thermal properties at all moisture levels. Silica fume concretes (compressive strength ≈ 27 MPa) incorporating 5, 10, and 15% silica fume gave the lowest values of thermal properties. At 0% moisture, the thermal conductivity values for the high-strength and the 5, 10, and 15% silica fume concretes were 1.64, 1.30, 1.28, and 1.30 W/°C-m, respectively. Their respective thermal diffusivity values were 91 x 10^{-4}, 83 x 10^{-4}, 80 x 10^{-4}, and 78 x 10^{-4} cm^2/s.

The increase in thermal conductivity and thermal diffusivity values with moisture content was relatively high for the high-volume fly ash concrete with 100 kg/m^3 of cement (compressive strength ≈ 17 MPa). The high-volume fly ash concretes with 180 kg/m^3 of cement (compressive strength ≈ 25 MPa) had low values of thermal properties at all moisture contents; the values of thermal conductivity and thermal diffusivity at 0% moisture were 1.32 W/°C-m and 81 x 10^{-4} cm^2/s, respectively. With 150 kg/m^3 cement (compressive strength ≈ 36 MPa) the high-volume fly ash concrete also had low values of thermal properties; at 0% moisture, the thermal conductivity and thermal diffusivity were 1.55 W/°C-m and 89 x 10^{-4} cm^2/s, respectively.

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3. "Mass Concrete" ACI 207.IR-87, ACI Manual of Concrete Practice, Part I, 1989.

Table 1- Physical Properties and Chemical Analyses of Cement, Fly Ash, and Silica Fume

	Portland Cement* (STM Type I)	Fly Ash**	Silica Fume
Physical Tests			
Fineness - passing 75 μm %	-	-	
- passing 45 μm %	92.8	82.7	
- Blaine, m^2/kg	-	289	
- Nitrogen adsorption, m^2/kg	-	-	20,000.00
Settingtime, min.			
- Initial	130	-	-
- Final	-	-	-
Autoclave expansion %	0.16	-	-
Compressive strength of 51-mm Cubes, MPa:			
3 - day	25.1		
7 - day	31.5		
28 - day	39.3		
Chemical Analysis			
Insoluble residue	0.20		
Silicon dioxide (SiO_2)	21.24	47.1	94.00
Aluminum oxide (Al_2O_3)	4.09	23.0	0.06
Ferric oxide (Fe_2O_3)	2.81	20.4	0.03
Calcium oxide (CaO), total	62.21	1.21	0.50
Calcium oxide (CaO), free	0.59	-	-
Magnesium oxide (MgO)	3.75	1.17	1.10
Sulphur trioxide (SO_3)	3.03	0.67	0.50
Sodium oxide (Na_2O)	-	0.54	0.02
Potassium oxide (K_2O)	-	3.16	0.20
Loss on ignition	1.64	2.88	2.50
Bogue Potential Compounds			
C_3S	51.63		
C_2S	22.03		
C_3A	6.09		
C_4AF	8.54		
Pozzolanic Activity with Portland Cement			
Water requirement, %		92	
Activity index at 28 days, %		98.2	
Accelerated activity index at 7 days, %		90.1	
Pozzolanic Activity Index with Lime at 7 days, MPa		6.8	

* Manufacturer's data
** CANMET data

Table 2 - Grading of Aggregates

Coarse Aggregate		Fine Aggregate	
Sieve Size	Cumulative Percentage Retained	Sieve Size	Cumulative Percentage Retained
19.0 mm	0.0	4.75 mm (No. 4)	0.0
12.7 mm	33.4	2.36 mm (No. 8)	10.0
9.5 mm	66.6	1.18 mm (No. 16)	32.5
4.75 mm	100.0	600 μm (No. 30)	57.5
		300 μm (No. 50)	80.0
		150 μm (No. 100)	94.0
		pan	100.0

Note: The grading of the aggregates was adjusted slightly for concrete mixture No. 10. The maximum size of coarse aggregate used was 12.7 mm.

Table 3 - Physical Properties of Aggregates

	Coarse Aggregate*	Fine Aggregate**
Specific Gravity	2.69	2.70
Absorption, %	0.82	1. 1

*Crushed limestone
**Natural sand

Table 4 - Concrete Mixture Proportions

Mixture Number	W* / C.M.	Quantities, kg/m^3							
		Water	Cement	Fly Ash	Silica Fume	Coarse Aggregate	Fine Aggregate	Superplasticizer	A.E.A.** mL/m
1	0.43	102	100	136	-	1112	910	7.2	213
2	0.32	115	152	209	-	1298	640	4.7	2502++
3	0.31	134	179	247	-	1209	569	2.8	369
4	0.43	101	99	135	-	1100+	900	6.6	139
5	0.32	115	152	209	-	1298+	639	6.5	446
6	0.32	136	180	249	-	1218+	574	2.9	373
7	0.55	152	262	-	14.1	1111	742	-	139
8	0.55	154	252	-	28.5	1160	711	-	175
9	0.56	155	237	-	40.9	1153	707	2.1	209
10	0.25	132	489	-	43.1	1117	685	17.7	-

* water-to-cementitious material ratio
** air-entraining admixture
\+ The coarse aggregate used was crushed granitic gravel in these instances
++ A sulphonated hydrocarbon type AEA was used in this mixture. In the other concrete mixtures a synthetic resin type AEA was used.

Table 5 - Properties of Fresh and Hardened Concrete

Mixture Number	Fresh Concrete				Hardened Concrete		
	Temperature °C	Slump mm	Unit Weight kg/m^3	Air Content %	Unit Weight at One Day kg/m^3	Compressive Strength, MPa 102 x 203-mm Cylinders	
						7 day	28 day
1	20	90	2365	5.2	2415	11.6	19.2
2	23	75	2415	3.4	2465	31.0*	36.7
3	21	130	2340	5.2	2375	14.9	24.2
4	15	90	2340	5.8	2370	8.9	14.9
5	25	200	2415	4.2	2460	22.0	34.8
6	22	110	2360	4.8	2390	15.6	25.6
7	22	50	2280	4.6	2295	17.4	24.1
8	22	40	2310	4.4	2315	20.7	27.6
9	22	60	2295	4.8	2320	22.6	28.8
10	24	180	2475	1.6	2520	68.7	84.2

* Strength determined at 14 days

Table 6 - Thermal Properties of Concrete

Mixture Number	Moisture Content, %														
	0			1		2		3		4		5		6	
	TC	TD	SH	TC	TD	TC	TD	TC	TD	TC	TD	TC	TD	TC	TD
1	1.44	84	0.170	1.67	91	1.89	98	2.07	104	2.19	106	-	-	-	-
2	1.56	89	0.171	1.75	95	1.96	101	2.08	105	2.13	98	-	-	-	-
3	1.32	81	0.165	1.52	88	1.72	94	1.90	99	2.06	102	2.18	103	-	-
4	1.39	83	0.170	1.62	92	1.84	100	2.05	105	2.17	108	2.34	108	-	-
5	1.55	89	0.169	1.72	94	1.90	98	2.04	100	2.13	99	2.17	97	-	-
6	1.35	83	0.164	1.53	89	1.73	94	1.92	100	2.05	101	2.12	100	-	-
7	1.30	83	0.164	1.45	87	1.60	91	1.72	94	1.84	94	1.93	95	1.99	93
8	1.28	80	0.172	1.45	85	1.62	89	1.75	92	1.85	93	1.90	92	1.92	89
9	1.30	78	0.178	1.45	81	1.60	85	1.76	89	1.92	93	2.04	95	2.14	95
10	1.64	91	0.172	1.82	95	2.00	100	2.19	104	2.38	108	-	-	-	-

Note: TC - Thermal Conductivity in $W/^{\circ}C\text{-}m$
TD - Thermal diffusivity in $cm^2/sx10^{-4}$
SH - Specific heat in $Cal/g.^{\circ}C$
Moisture content is given as a percent of dry weight

Table 7: Typical Variations in Thermal Conductivity with Moisture at Normal Temperatures

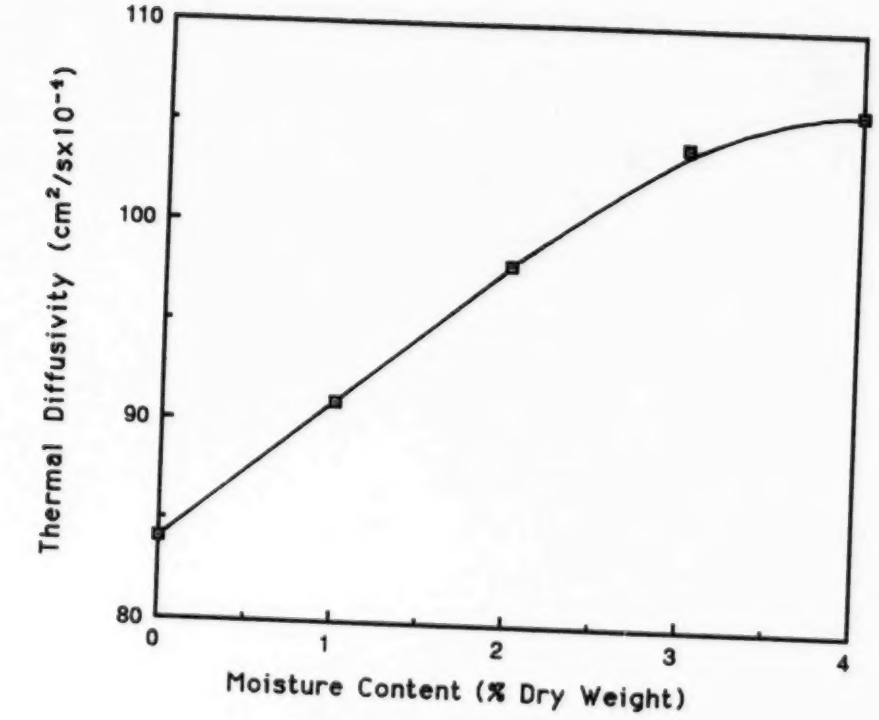
Concrete Type	Thermal Conductivity (W/°C-m)		
	Dry Condition	50% Relative Humidity	Moist Condition
Limestone Concrete	1.44	1.59	2.16
Sandstone Concrete	1.44	2.16	2.88
Quartz gravel Concrete	2.31	2.74	3.32
Expanded Shale Concrete	0.62	0.79	0.85
Granite Stone Concrete	--	--	2.59

From Ref. 1

Table 8: Thermal Properties of some Mass Concretes in Dams.

Structure	Coarse Aggregate Type	Temperature °C	Density kg/m^3	Thermal Conductivity W/°C-m	Thermal Diffusivity $cm^2/sx10^{-4}$	Specific Heat cal/g°C
Angostura	Limestone	38	2423	2.56	105.6	0.237
Libby	Natural Quartz gravel	36	2435	3.86	172.2	0.220
Hoover	Limestone and granite	38	2500	2.89	122.2	0.225
Hungry Horse	Sandstone	38	2406	2.94	127.8	0.232
Flaming George	Limestone and Sandstone	38	2411	3.03	127.8	0.234

From Ref. 3



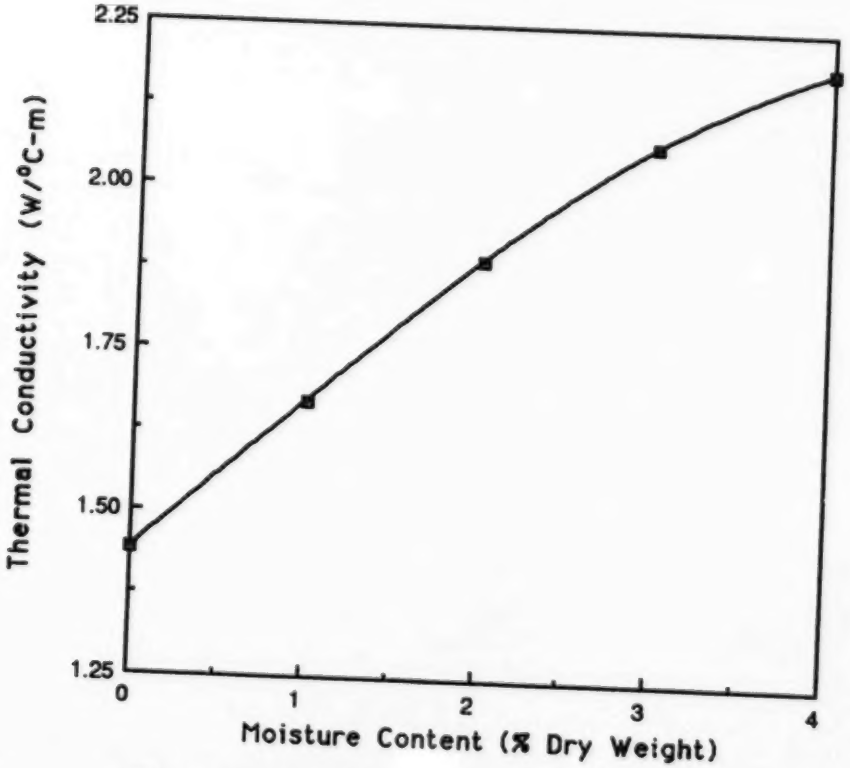
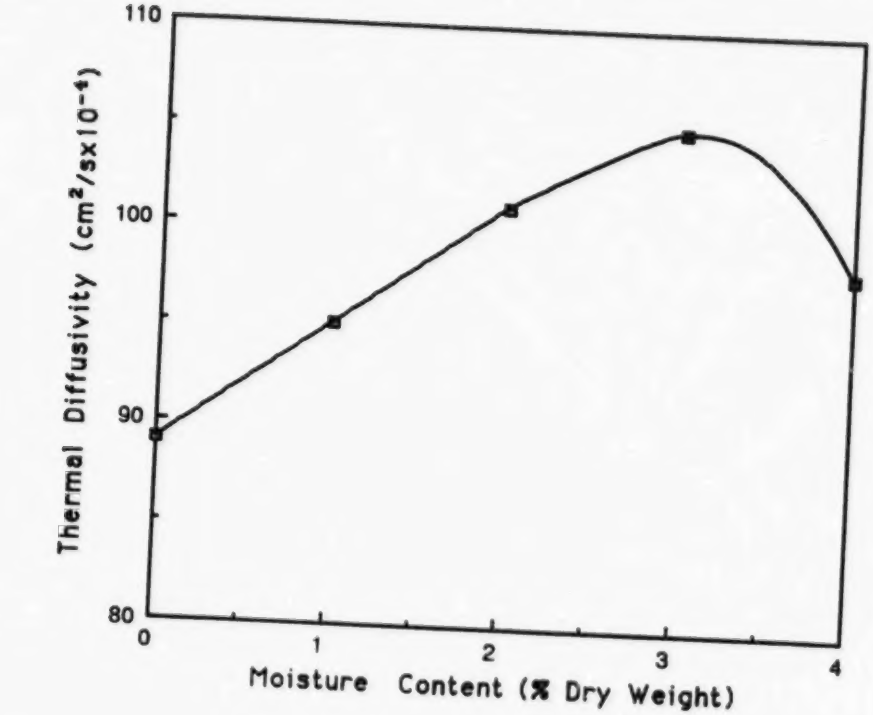


Fig.1. Thermal Properties vs Moisture Content for Concrete No.1



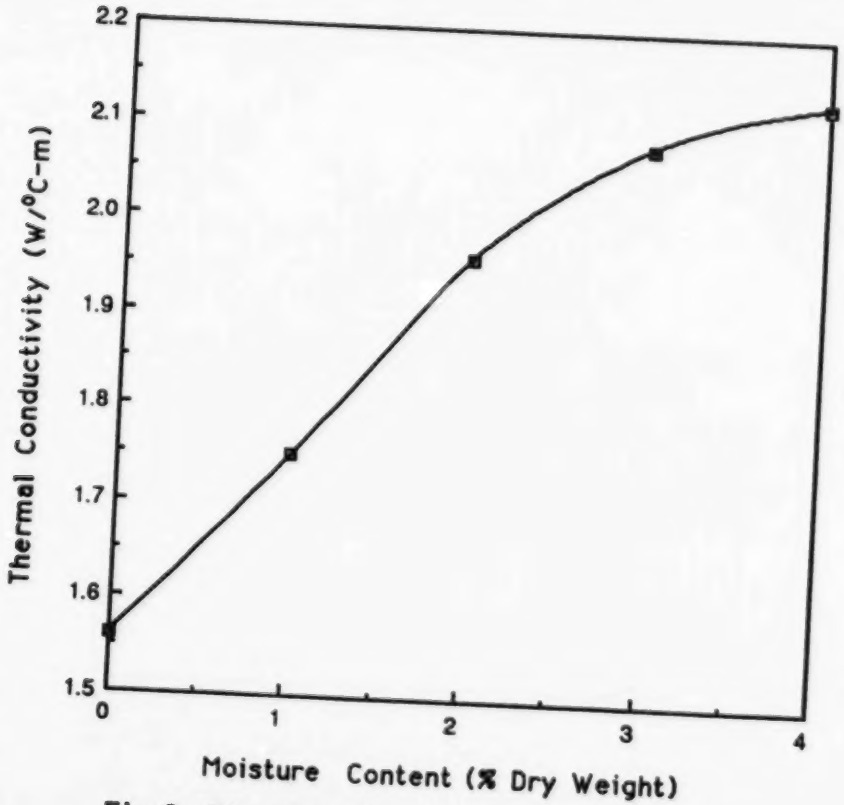
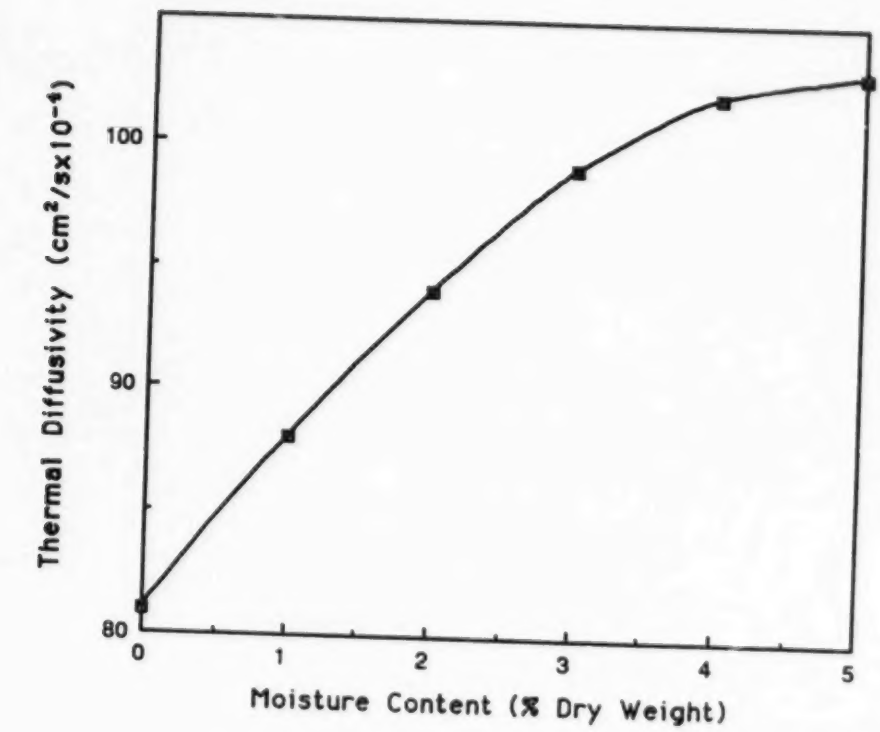


Fig.2. Thermal Properties vs Moisture Content for Concrete No. 2



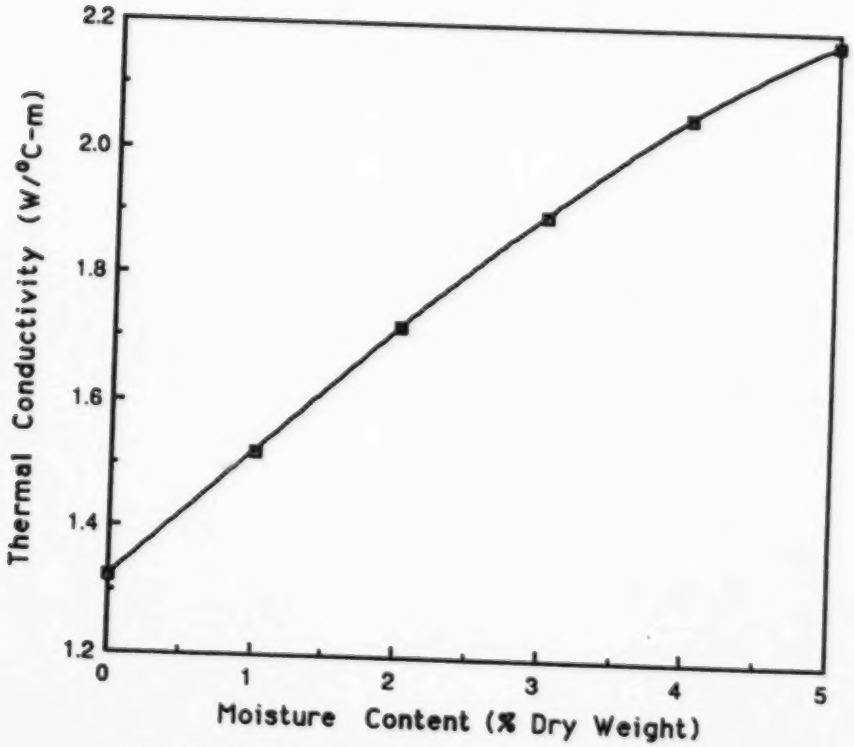
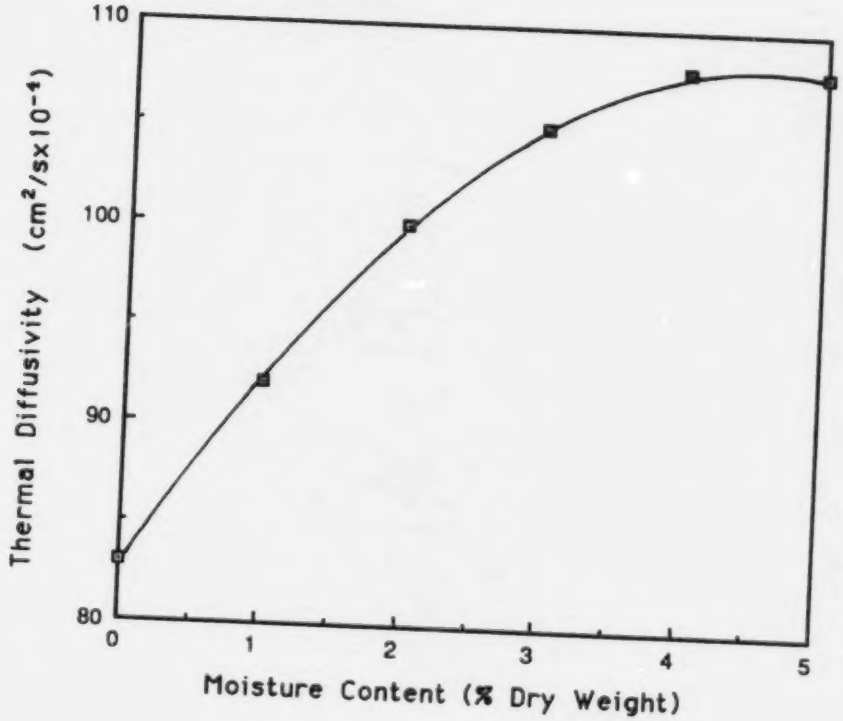


Fig.3. Thermal Properties vs Moisture Content for Concrete No.3



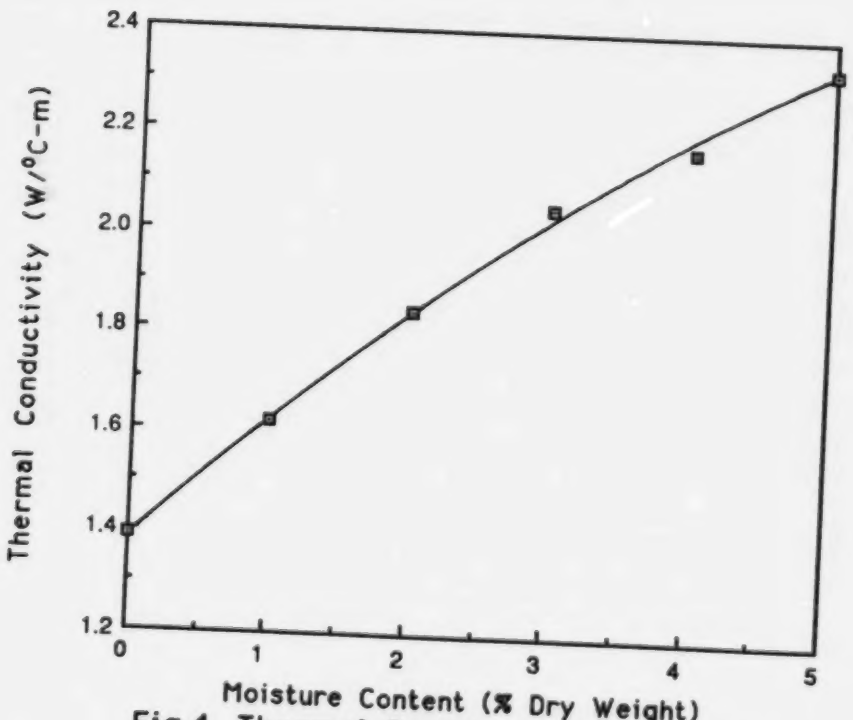
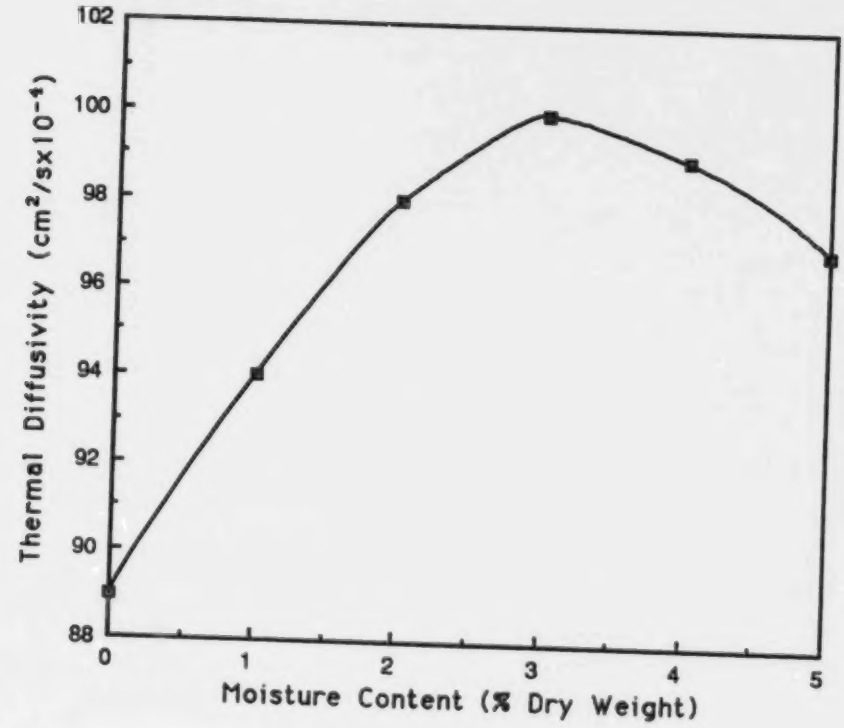


Fig.4. Thermal Properties vs Moisture Content for Concrete No.4



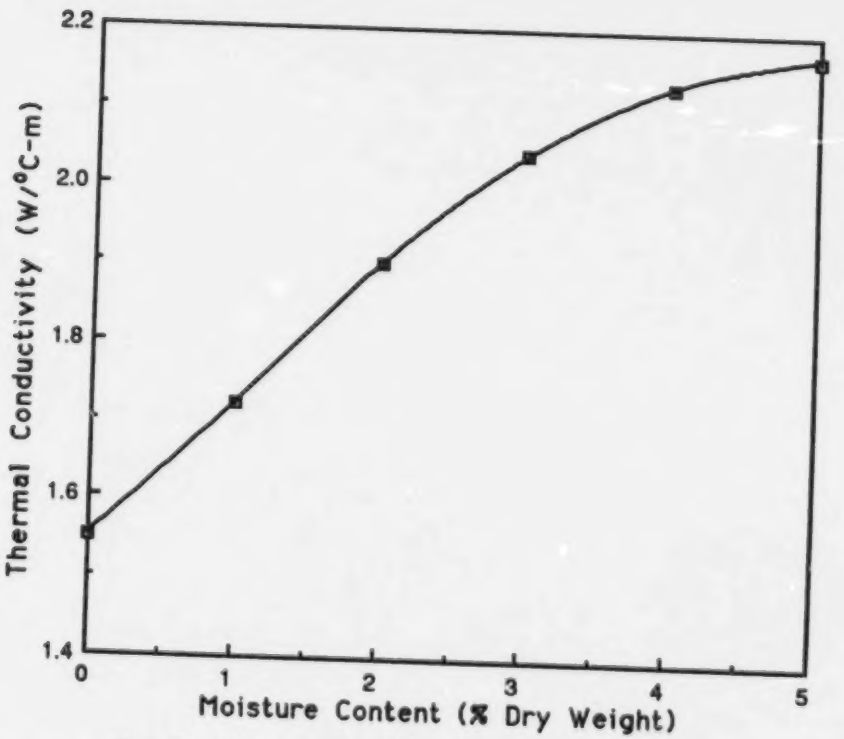
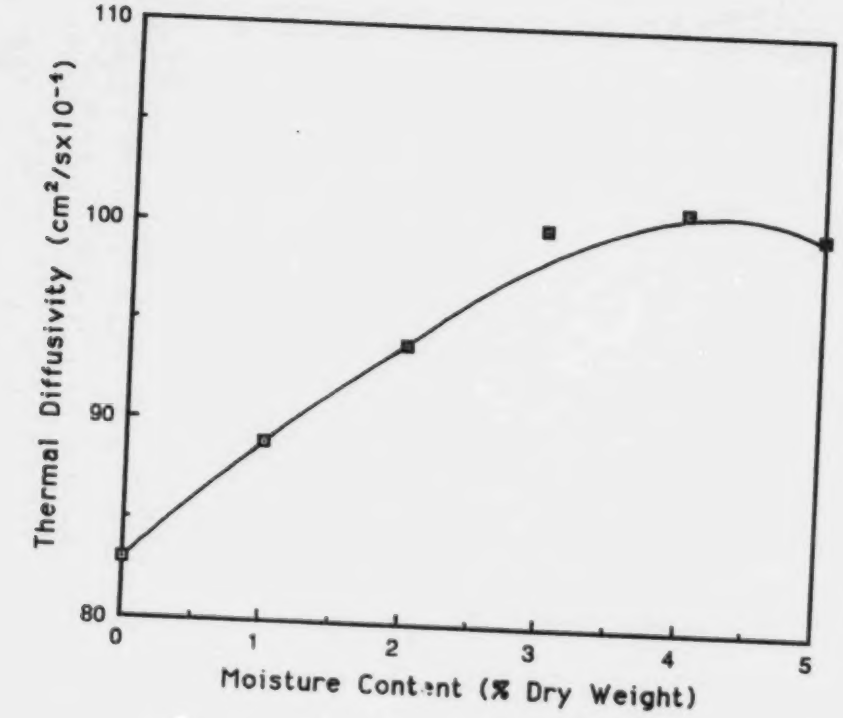


Fig.5. Thermal Properties vs Moisture Content for Concrete No.5



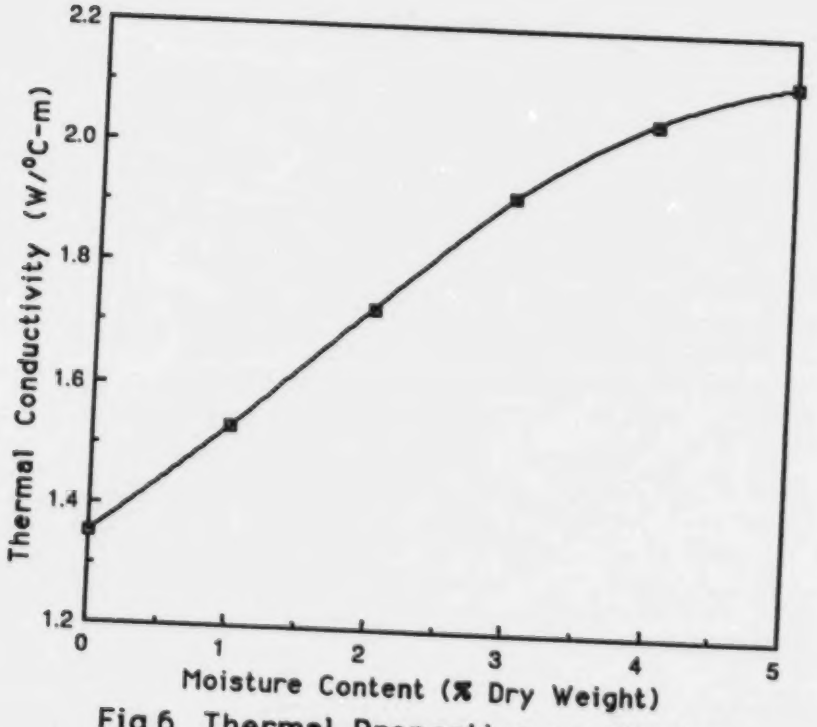
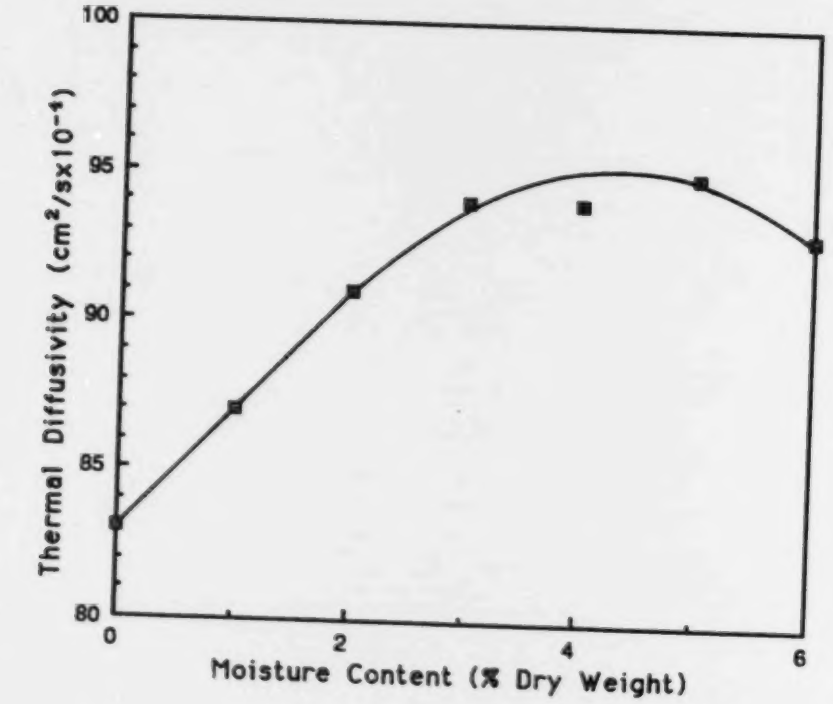


Fig.6. Thermal Properties vs Moisture Content for Concrete No. 6



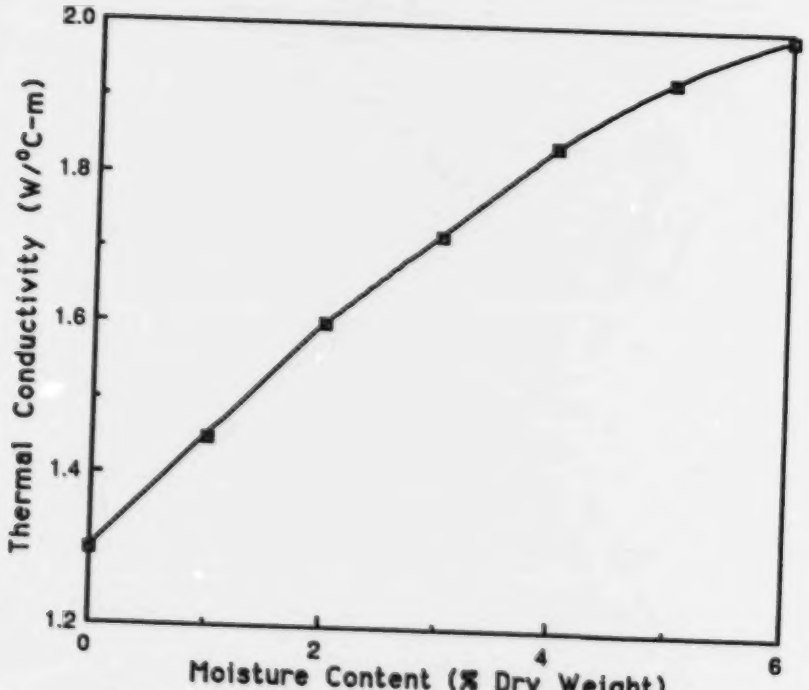
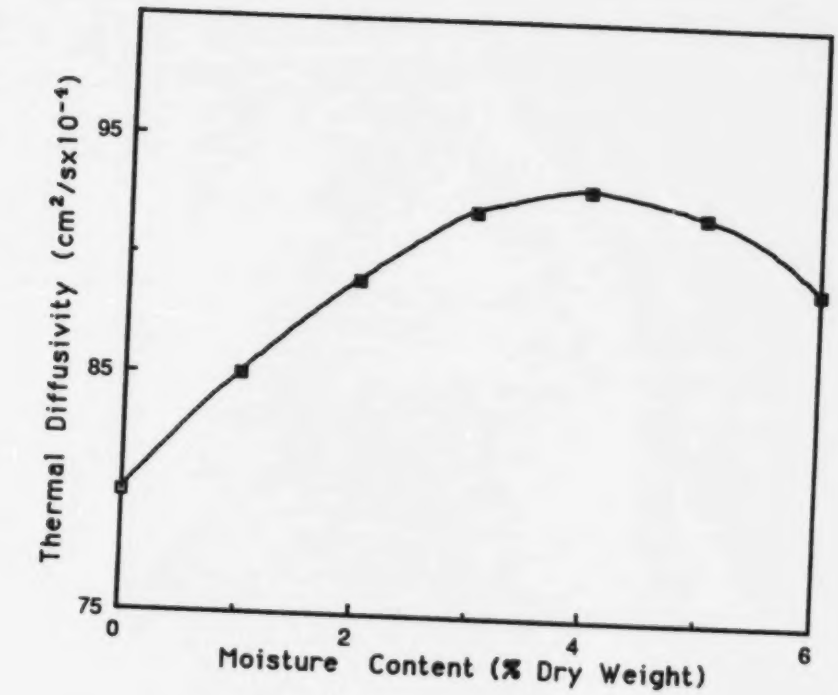


Fig.7. Thermal Properties vs Moisture Content for Concrete No.7



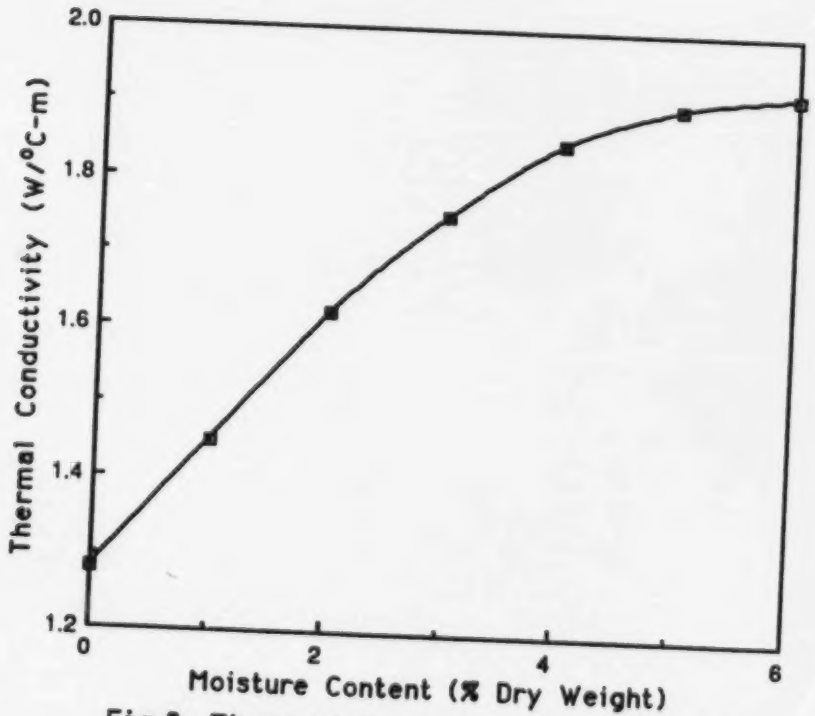
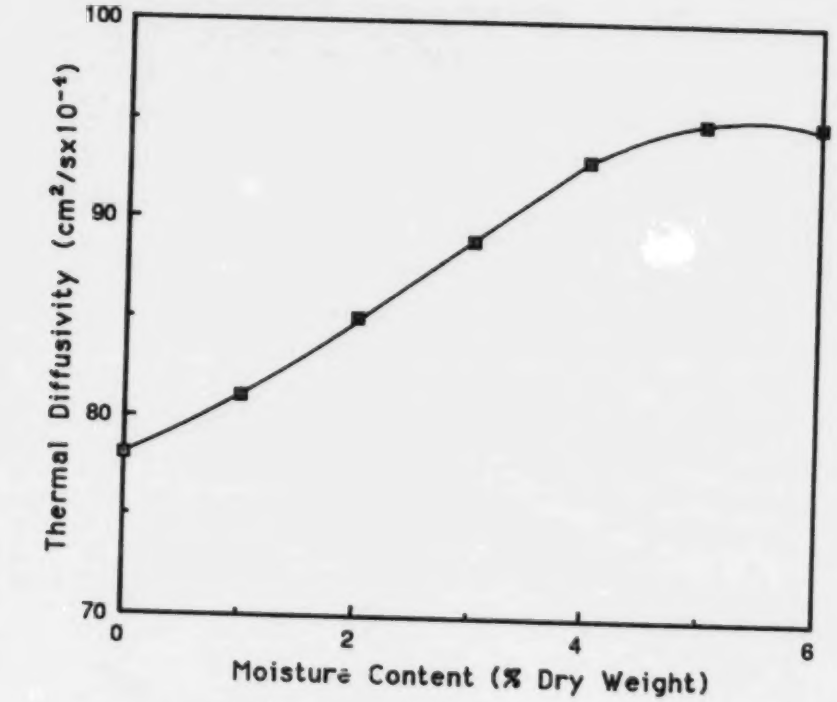


Fig.8. Thermal Properties vs Moisture Content for Concrete No.8



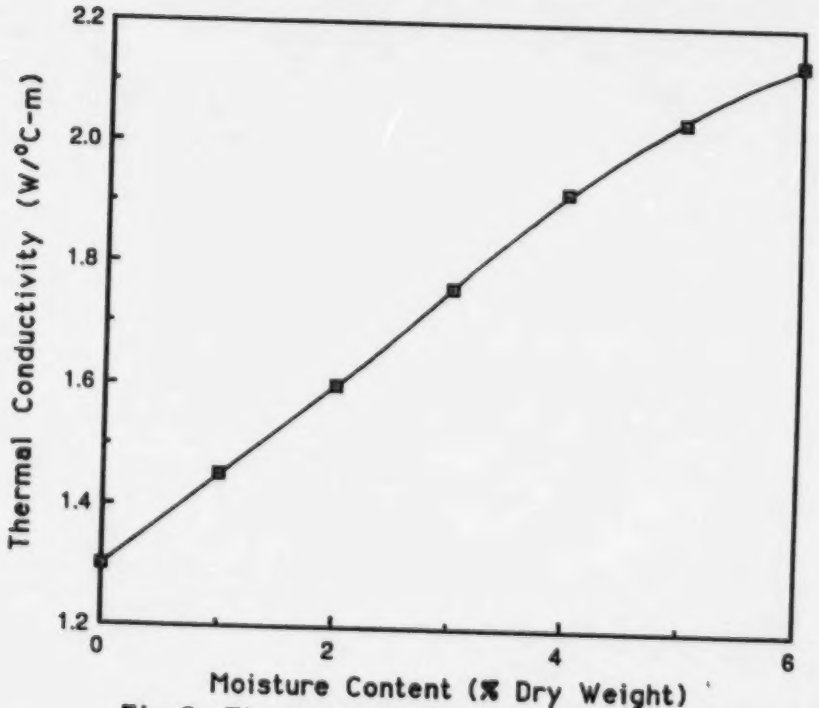
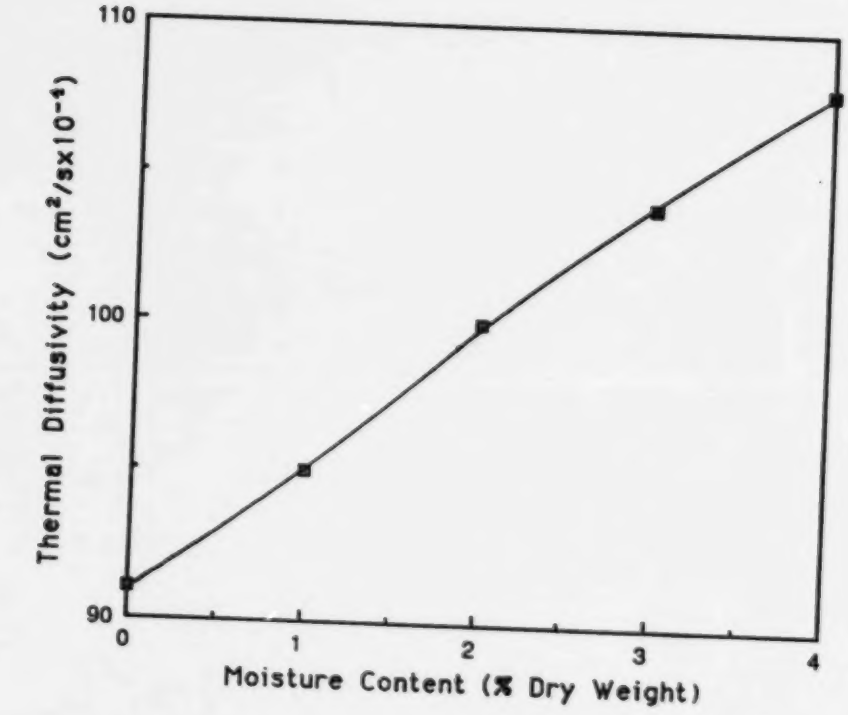


Fig.9. Thermal Properties vs Moisture Content for Concrete No.9



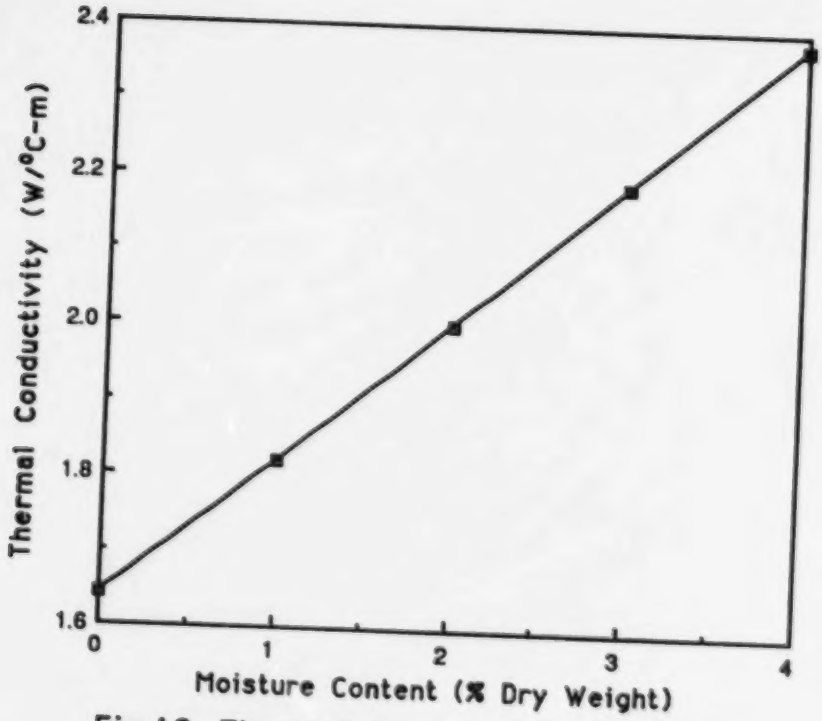


Fig.10. Thermal Properties vs Moisture Content for Concrete No.10

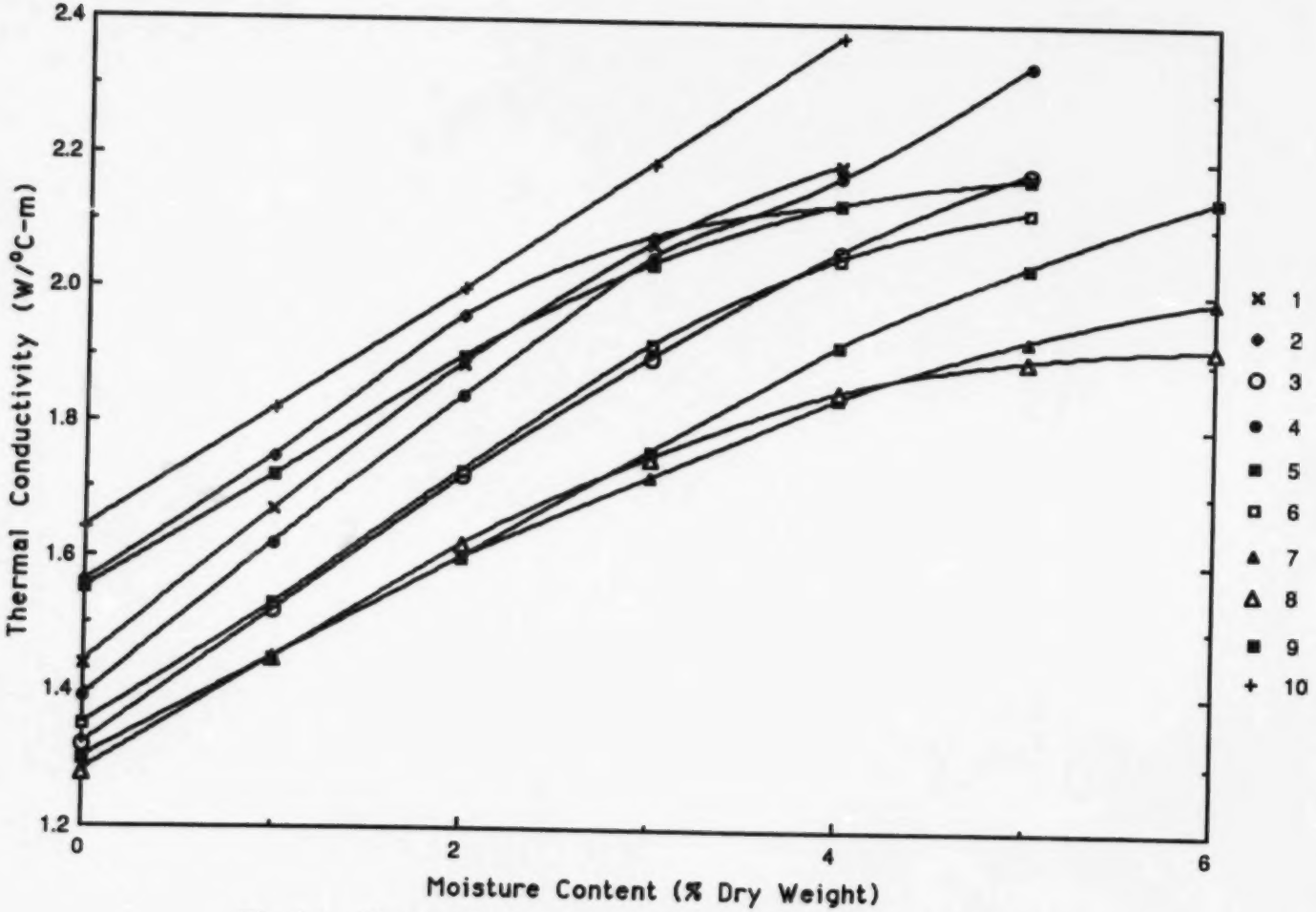


Fig.11. Thermal Conductivity vs Moisture Content for Concretes No.1 to 10

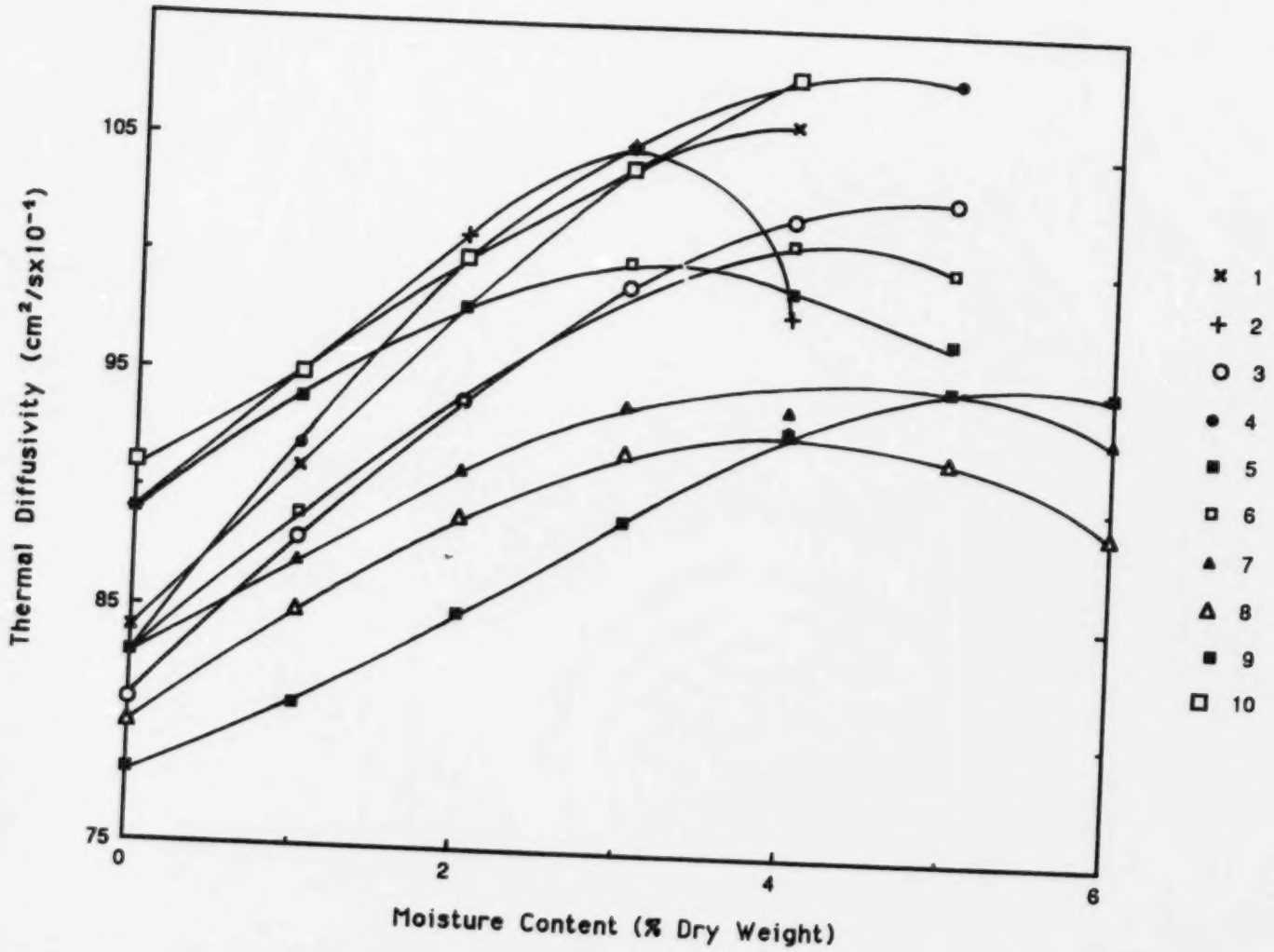


Fig.12. Thermal Diffusivity vs Moisture Content for Concretes No.1 to 10

APPENDIX

Underground Cable Thermal Backfill

Pergamon Press, Toronto, 1982

THERMAL PROPERTY MEASUREMENTS USING A THERMAL PROBE

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ABSTRACT

The transient thermal probe is a relatively quick method of measuring soil thermal properties. Accurate test results can be obtained with correct test procedures, proper probe construction and calibration, and an understanding of the limitations of the transient thermal probe method. Undisturbed Shelby tube soil samples can be used for laboratory testing. The transient thermal probe method is used to determine thermal resistivity, and the Shannon and Wells method to determine thermal diffusivity. The use of large diameter probes for field thermal testing requires even greater consideration of theoretical assumptions.

KEYWORDS

Soil thermal property measurements; thermal resistivity; thermal diffusivity; transient thermal probe method.

INTRODUCTION

The transient thermal probe is a relatively quick method of measuring the thermal properties of soils and gives accurate results provided the theoretical assumptions are understood and care is taken in the test set-up to stay within the realm of the theory. The transient method has the advantage over steady state methods that a single measurement can give not only the thermal resistivity but also the thermal diffusivity and thermal stability (Boggs and others, 1980).

The transient probe method is based on the theory of the infinite line heat source (Carslaw and Jaeger, 1959) which predicts that the temperature as a function of time at a distance "r" from an infinite-line heat source dissipating "q" power per unit length into a medium of thermal resistivity "ρ" and thermal diffusivity "α" is:

$$T(t) = \frac{-q\rho}{4\pi} \mathrm{Ei}\left(\frac{-r^2}{4\alpha t}\right) \qquad (1)$$

which can be expanded in the form:

$$T(t) = \frac{-q\rho}{4\pi}\left[\ln\frac{4\alpha t}{r^2} - \gamma + \frac{r^2}{4\alpha t} - \frac{1}{4}\left(\frac{r^2}{4\alpha t}\right)^2 + \frac{1}{9}\left(\frac{r^2}{4\alpha t}\right)^3 - \frac{1}{16}\left(\frac{r^2}{4\alpha t}\right)^{4+} \ldots\right] \qquad (2)$$

where γ is Euler's constant 0.5772

If only the first term is kept, one obtains:

$$T(t) = \frac{q\rho}{4\pi} \left[\ln \left(\frac{4\alpha t}{r^2}\right) - \gamma\right] \tag{3}$$

which can be rearranged in the form:

$$T(t) = \frac{q\rho}{4\pi} \left[\ln t + \ln \frac{4\alpha}{r^2} - \gamma\right] \tag{4}$$

from which it becomes apparent that if temperature is plotted as a function of ln(t), the slope is $q\rho/4\pi$, from which the thermal resistivity can be determined. (Fig. 1)

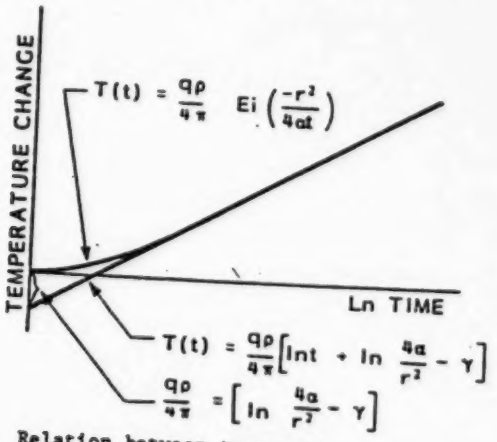


Fig. 1 Relation between temperature rise, time, and soil thermal parameters

Blackwell (1954) developed an approximate solution for a hollow cylindrical probe which is very close to the line heat source equation:

$$T(t) = \frac{q\rho}{4\pi} \left[\ln t + \ln \frac{4\alpha}{r^2} - \gamma + \frac{2}{\rho r H}\right] \tag{5}$$

where H is the contact conductance at the probe-soil interface.

From the above, the thermal diffusivity may be obtained by the intercept method. If I is the intercept of the straight line extrapolated back to the ln t axis, then:

$$\alpha = \frac{r^2}{4} \exp \left[\gamma - \frac{2}{rH\rho} - I\right] \tag{6}$$

To a first approximation, the term $2/rH\rho$ can be ignored if a large radius probe is used and the contact between the soil and the probe is good.

For test results to agree with the above theoretical predictions the experimental procedures should comply with the major assumptions, namely:

i) the probe is an instantaneous and constant source of heat

ii) flow of heat is radial

iii) test data is free from the sample boundary effects

iv) no thermal contact resistance exists between the heat source and the soil

v) conduction is the only mechanism of heat transfer

vi) test material is homogeneous, and a moisture and thermal equilibrium exists in the sample before the test.

EQUIPMENT

The criteria of constant and true cylindrical source of heat are better approximated with the use of quality equipment. The major components of the equipment package are the power supply, the temperature reader, and the thermal probe.

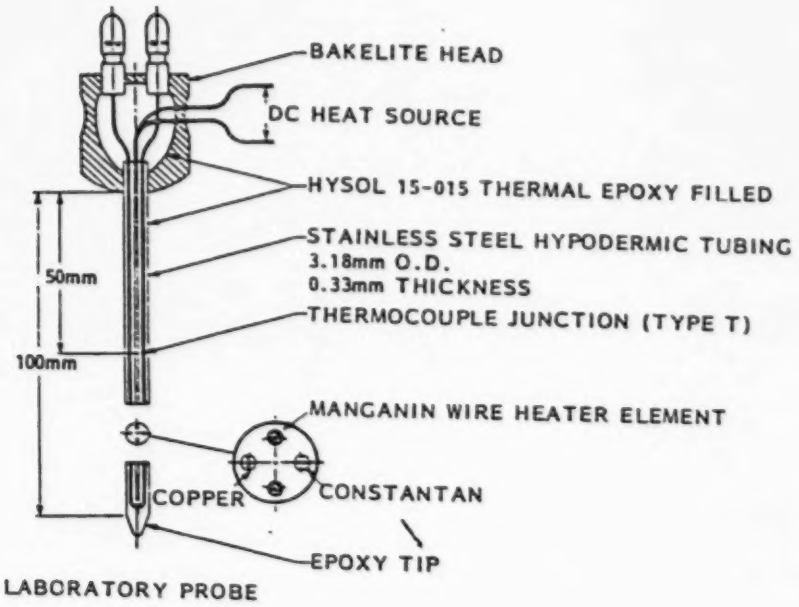
Mitchell and Kao (1978) demonstrate the effect of an unstable current source. They indicate that a small variation (1-2%) in the current output from the power supply can have a large effect on the thermal resistivity (-18%). Their concern is with the use of storage batteries which can have variations in the current output. Our experience is that a good quality stabilized DC power supply run off an AC generator in the field, or AC main line in the laboratory is able to deliver constant current.

A temperature reader (thermocouple reader in most cases) that drifts excessively due to environmental conditions (heat, air current) will produce inconsistent results. In field applications it is especially important that the thermocouple reader be shielded from environmental effects since the sun's heat may cause a drift in the isothermal reference junction in the compensation circuitry. In laboratory applications a properly maintained ice bath reference for the thermocouples gives the most consistent results.

Any shortcomings in the equipment are magnified in the field where conditions are harsher than in the laboratory environment. Ontario Hydro uses the Thermal Property Analyzer (Boggs and others, 1980), which is a microprocessor controlled unit that provides a stable power source and stable thermocouple readings in addition to automating the whole process of running a thermal resistivity test.

A properly constructed thermal probe is essential and exacting standards are to be met with regards to: thermocouple placement, uniformity of cross section along the length of the probe, proper insulation against electrical shorts, heater resistance and length measurements, and mechanical durability. Wechsler (1966) investigated the design of the thermal probe and made recommendations about the construction technique. The probes used by Ontario Hydro (Fig. 2) are similar to these. It is important to note that the heater should be as close to the sheath as possible, with the measuring thermocouple also located at the interior wall of the sheath. An epoxy filler of low thermal resistivity minimizes the initial transient time to valid test points. A stainless steel sheath provides good structural rigidity as well as minimizing interference with radial heat flow.

In order to ensure that axial heat flow is insignificant for the duration of the test, the probes must have a sufficient length to diameter ratio. Blackwell (1954) provides the methodology for choosing an appropriate ratio based on his theoretical analysis.



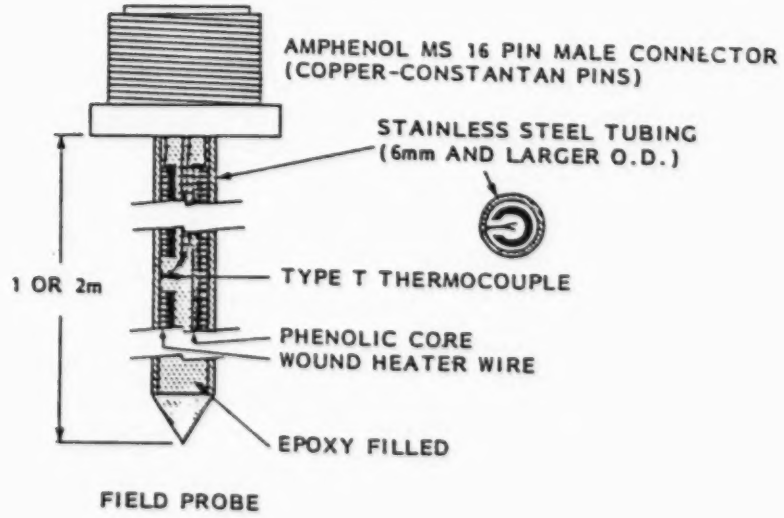


Fig. 2 Thermal probes

CALIBRATIONS

Several checks and calibrations are to be performed on the probes to validate them for use. The total resistance of the heater should be measured and compared to that specified. If it is not as expected, it will result in an incorrect calculation of probe power, and thus thermal resistivity. Resistance can be determined by external measurement, but the heater length cannot be assumed the same as the probe length. The length of the heater can be determined by attaching external thermocouples, heating the probe, and noting at which point the temperature ceases to rise dramatically. Checks for heater-thermocouple and heater-sheath shorts are simple, and resistances between the above components should exceed 10 kΩ.

The thermal probes can be calibrated in laboratory standard materials, such as glycerol, or against other standard techniques, such as the guarded hot plate (ASTM C177). The advantages of glycerol are twofold. Being a liquid, the probe thermal contact is extremely good and contact resistance-related errors can be neglected. Also, since glycerol is viscous, convective heat flow is negligible as long as the test temperature rise is kept small (less the 5°C). The experimental result may be compared to the published value (349°C-cm/W at 20°C) and any discrepancy can be corrected with a multiplying factor. Furthermore, calibration liquids can be found to cover the expected range of soil thermal resistivities.

If the internal thermocouples are not in perfect contact with the probe sheath, the actual probe radius may not be the correct parameter to use in the intercept method of thermal diffusivity calculation. The 'effective radius' of a probe may be determined by using the temperature versus time data for a glycerol run in the TDFIT computer program (Boggs and others, 1980) and varying the probe radius until the calculated thermal diffusivity matches the published value for glycerol (9.4×10^{-4} cm^2/sec at 20°C). The TDFIT program, which was developed by Ontario Hydro, is based on Blackwell's (1954) solution of the heat diffusion equation for a cylindrical probe having finite heat capacity and contact conductance.

The probe heat capacity can be determined from a very low power thermal resistivity run (less than 1 C° temperature rise over 500 seconds) in a good thermal insulator such as foam rubber. Now from the straight line portion of the temperature vs time (not log time) plot:

$$C = \text{POWER} \times \frac{\Delta \text{time}}{\Delta \text{temp}}$$

High probe heat capacity may cause excessively long initial transient times.

PROBE TO SOIL THERMAL CONTACT RESISTANCE

When a probe is inserted in an undisturbed sample, the probe to soil contact becomes an important factor. In practice, the major deviation from the theoretical probe response is caused by the thermal contact between the probe and soil. If the probe had no heat capacity, this would cause only an instantaneous offset in the temperature when probe power is initiated. Because of probe heat capacity, the contact-related temperature rise gradually approaches the offset value. Whereas the effect of probe heat capacity is predictable, the contact conductance depends on the soil under test and the skill of the operator in installing the probe with minimum disturbance. The diameter of the thermal probe can affect the magnitude of the thermal contact resistance effects. That is, for the same given amount of disturbance, a smaller diameter probe will "see" a larger volume of voids relative to its surface area, therefore the time to overcome the contact disturbance will be greater.

Poor probe to soil contact results in a longer time to approach the straight line portion of the curve (ie initial transient time). For the determination of ther-

mal resistivity this will delay the formation of the straight line portion of the data, but not change the absolute value of the thermal resistivity which is derived from the slope of that straight line (Fig. 3). However, for the thermal diffusivity determination with the intercept method, the contact resistance offset is crucial, because the diffusivity depends on both the slope and intercept. Only if the probe radius is sufficiently large, and the contact is good, can the intercept method give a reasonable value of thermal diffusivity.

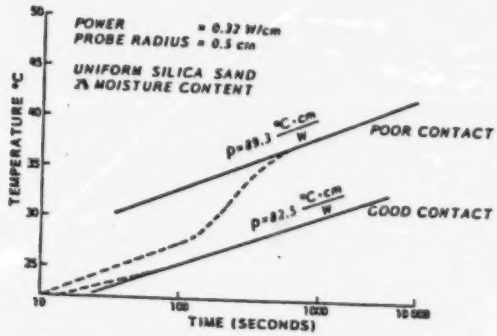


Fig. 3 The effect of probe to soil thermal contact resistance on the determination of soil thermal resistivity and diffusivity

LABORATORY THERMAL RESISTIVITY TEST

In the laboratory, Ontario Hydro attempts to simulate field conditions, therefore the standard procedure is to retrieve relatively undisturbed tube samples of soil rather than loose samples that have to be reconstituted for a test. The 76 mm (2-7/8 inch) diameter Shelby tube sample has proven to be sufficient for our applications and efforts in standardizing testing procedures have been based on it. From a single set-up it is possible to run the transient thermal resistivity test and the Shannon and Wells thermal diffusivity test.

In relatively homogeneous Shelby samples the 3.2 mm (1/8 inch) diameter needle works well in that it has fairly good strength for pushing into stiff materials and contact problems are usually of a manageable magnitude. While a smaller diameter needle, such as 1.6 mm (1/16 inch), has a greater chance for poor thermal contact it has an advantage in materials that contain stone size particles (such as tills). In this case the finer needle may slip in more easily between the larger stones, whereas the larger probe may catch on these particles and not be able to be inserted at all.

In softer soils a needle can be inserted by hand. In variable soils it is difficult to hold the probe steady and a large amount of distortion in the hole may occur. In practice, the probes should be held by a jig that will keep everything stable while the probe is pushed in. In very stiff soils, it may be necessary to drill a pilot hole; however, the resulting probe to soil thermal contact is usually poor. Care must be taken to ensure that small probes are not inadvertently moved during a test, resulting in distortion of the thermal field and invalid data.

Even if exceptionally good contact is achieved, say by packing the soil around the probe, an initial transient will be evident in the temperature vs log time curve due to probe properties such as; finite diameter, thermal resistivity and heat capacity of the probe materials. Hartley and Black (1976) have produced curves,

based on Blackwell's theory, that indicate minimum transient times taking the above factors into consideration. Of course, poor probe to soil contact will result in a much longer time but these calculated transient times along with estimates of sample boundary time effects can be used as an aid in selecting the portion of the experimental curves to use for thermal resistivity calculations.

SAMPLE BOUNDARY EFFECTS

The theory for the transient thermal resistivity test is based on an infinite sample size, therefore if a sample of given radius is used boundary effects will become evident after a certain time. The actual test results must be separated from these effects. According to de Vries and Peck (1958), this time can be estimated from

$$\exp(-R^2/4\alpha t) \ll \phi \qquad (7)$$

where R = sample radius
α = sample diffusivity
t = time
ϕ is <<1, say 0.02 (Wechsler, 1966).

In practice this appears to give the time when the thermal front first impinges on the boundary. It takes a longer time for these boundary effects to cause a deviation at the thermal probe. By placing a thermocouple at the soil-container boundary and monitoring it along with the thermocouple in the probe the relationship between theoretical calculation, test effect, and boundary effect may be observed (Fig. 4). The 76 mm diameter tube sample has proved to be sufficient for materials with thermal resistivities greater than about 45°C-cm/W (ie as thermal resistivity increases, the time for the boundary effects to invalidate the results becomes longer). The value of 45°C-cm/W is based on the fact that the initial transient time before the straight line may be 200 to 300 seconds and for a 76 mm Shelby tube the edge effects become evident at about 700 to 800 seconds. At lower thermal resistivities the initial transient time and boundary effects time may become too close to choose a proper straight line for the thermal resistivity calculation.

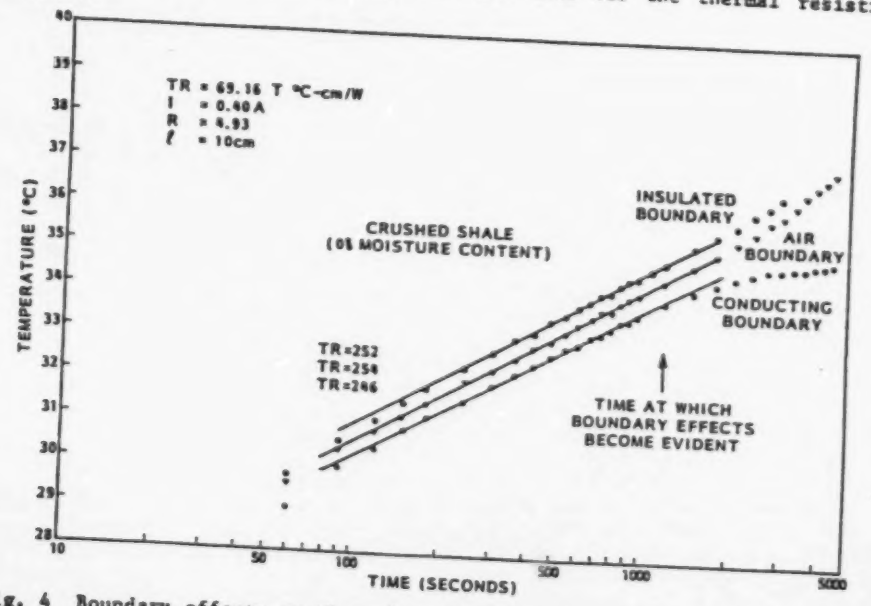


Fig. 4 Boundary effects on thermal resistivity tests in Shelby tube samples

Thermal Property Measurement

It is helpful to know the effects of different boundary conditions on the experimental curve. The temperature vs time curve swings upwards if the boundary is insulated whereas it levels off for a conducting boundary (such as a stirred water bath). Air behaves like an insulating boundary. The thermal resistivities determined from the straight line portion of the test data for each of the boundary conditions are fairly close (Fig 4).

STAGE DRYING TEST

A discrete thermal resistivity at a particular moisture content is insufficient information for most applications as in situ soil moisture and thus thermal resistivity continually change. A stage drying test must be performed on the Shelby tube samples to fully characterize the thermal behaviour of the soil. Figure 5 shows characteristic curves of thermal resistivity vs moisture content for different types of soils.

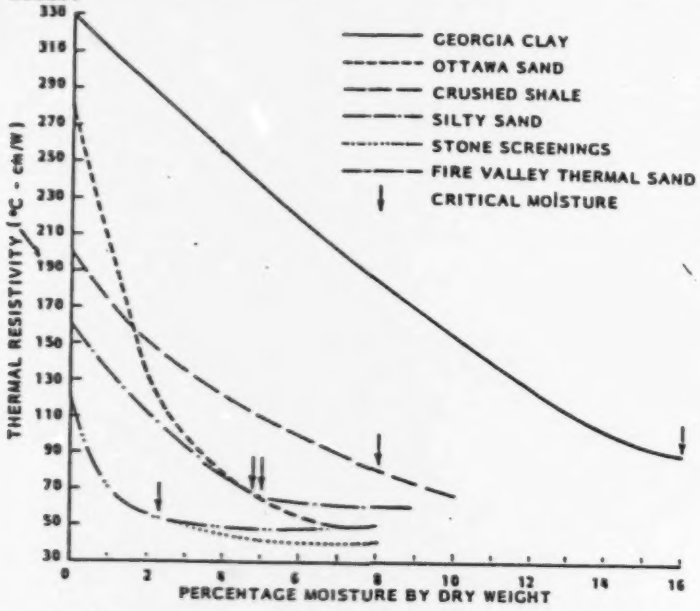


Fig. 5 Thermal resistivity vs moisture content

The sample and tube may be cut into sections in order to measure the thermal resistivity as a function of depth. The laboratory probe is left inserted and the sample air and oven dried in stages to obtain the thermal resistivity as a function of moisture content. After each drying stage the sample must be sealed (plastic wrap) and allowed to cool (if oven dried), and equilibrate with respect to spatial moisture distribution (requiring several hours for a granular soil, at least overnight for silty soils, and even longer for clayey soils) prior to measuring thermal resistivity.

The importance of sample equilibrium cannot be over-emphasized. If a sample is moved from a cooler to warmer environment it must be given time to come to ambient conditions. This can be monitored with the thermal probe. The samples must be wrapped in plastic because surface evaporation during a test may cause enough cooling to give erroneous results.

The amount of input power to the probe and hence the soil must be carefully selected to insure that conduction is the only mechanism of heat transfer. If the

probe heats up too much, moisture migration will be induced. Conversely if there is too small a temperature rise there will not be a clear definition in the experimental curve. In general, the standard 1000 second thermal resistivity test should have a total temperature rise above ambient of about 6 to 10 C°.

SHANNON AND WELLS THERMAL DIFFUSIVITY TEST

The Shannon and Wells thermal diffusivity test was adapted for use with Shelby tube (76 mm) samples using a thermal probe as the passive temperature sensor. This type of set-up would allow tests to be carried out on an undisturbed sample for both thermal resistivity and thermal diffusivity. The Shelby tube samples are prepared as in Fig. 6. Care must be taken to centre the thermal probe and to seal the tube ends properly since the sample will be immersed in a water bath.

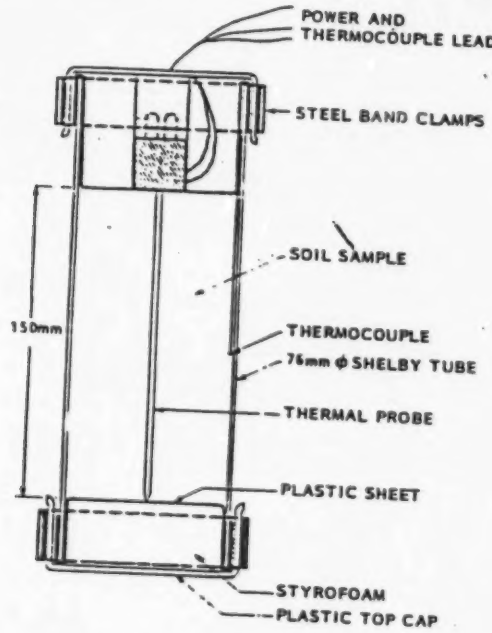


Fig. 6 Shannon and Wells thermal diffusivity test using a Shelby tube sample

The samples are allowed to equilibrate at a constant elevated temperature overnight in an oven. This temperature should only be about 8 C° above the ambient room temperature. If the samples are preheated to too high a temperature the thermal gradients induced after their immersion in the water bath would cause moisture migration in the soil sample and the attendant convection of heat would disrupt the measurement of thermal diffusivity. An 8 C° rise in temperature is enough to provide good definition of the cooling curve for the Shannon and Wells analysis.

The warm samples are transferred to a constant room temperature circulating water bath and the temperature and time of the thermal probe are monitored. The resultant plots of temperature vs log time (Fig. 7) are analyzed by the theory of Shannon and Wells (1947) to calculate the thermal diffusivity.

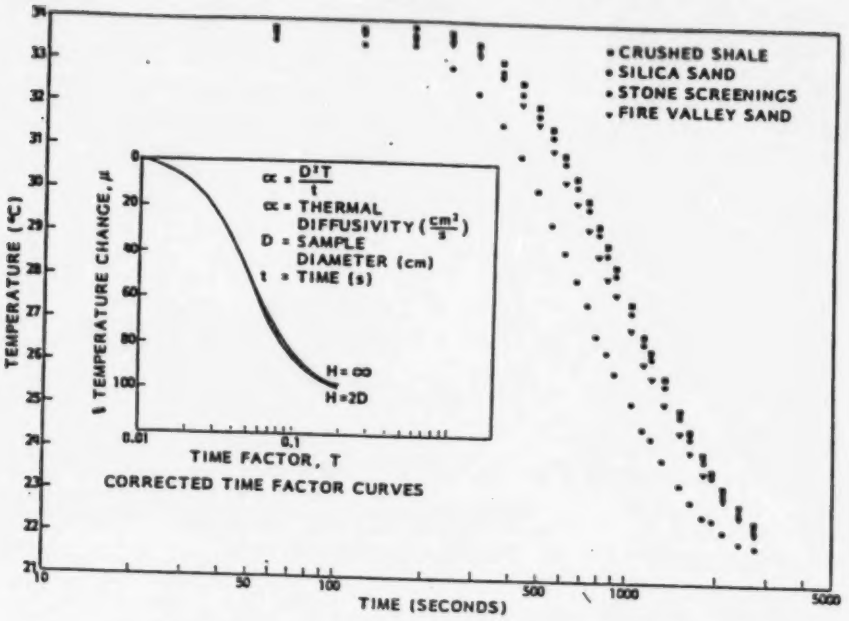


Fig. 7 Shannon and Wells thermal diffusivity test on dry soils.

TABLE 1 Shannon and Wells Test Results

Dry Soil	Time for 50% Change in Temperature(s) t	$\alpha = \frac{D^2T}{t}$ $(\frac{cm^2}{s})$	γ_d $(\frac{g}{cm^3})$	ρ $(\frac{°C-cm}{W})$	$c = \frac{1}{\rho\alpha\gamma_d}$ $(\frac{J}{g-°C})$
Crushed Shale	990	0.0025	1.9908	254	0.79
Silica Sand	960	0.0026	1.8339	300	0.70
Fire Valley Sand	910	0.0027	1.8113	264	0.77
Stone Screenings	710	0.0035	2.1609	127	1.04

*Diameter (D) = 7.0 cm, Time Factor (T) for 50% = 0.05, D^2T = 2.45

Thermal resistivity (ρ) and thermal diffusivity (α) are related by the expression:

$$C = \frac{1}{\rho\alpha} \tag{8}$$

where C is the volumetric heat capacity.

For a dry soil

$$C = \gamma_d \cdot c \tag{9}$$

where c is the specific heat of the soil solids.

Thus $c = 1/\rho\alpha\gamma_d$. (10)

The experiment was performed on four representative dry soil samples for the measurement of both the thermal diffusivity and resistivity. Table 1 summarizes the thermal diffusivity and the specific heat values calculated from the above equation. The specific heat of soil solids can be generally considered to be in the range of 0.8 [J/g-°C] (Shannon and Wells, 1947). The experimental results fall very close to this (with the exception of stone screenings) indicating that the two thermal property measurements give reasonable and compatible results.

FIELD TESTING

Field probes have been used in 1 and 2 m lengths and diameters of 6, 10, and 25 mm. For the larger diameter probes, the deviation from the theory becomes greater and more emphasis has to be placed on probe calibration and applying necessary corrections to the results.

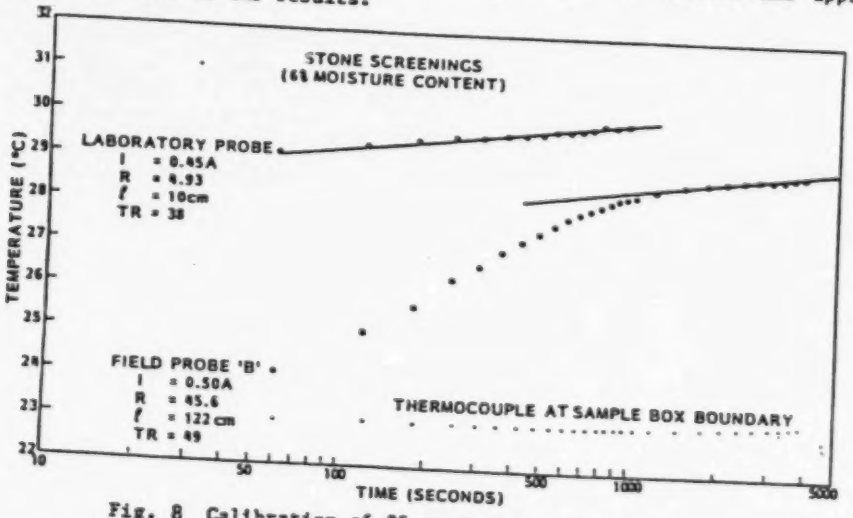


Fig. 8 Calibration of 25 mm diameter field probe

The field probes will contain quite a large volume of filler material and therefore the heat capacity of the probe will be rather significant. Combined with the thermal contact resistance effects this will extend the initial transient time significantly. Certain 25 mm diameter probes when checked in the laboratory were found to have an initial transient time in the order of 1500 seconds (Fig. 8). In such a case the thermal resistivity test must be extended to between 2000 and 3000 seconds and only the points after 1500 seconds used for thermal resistivity calculations. Thermal diffusivities calculated from such data by the intercept method are not valid.

Thermal Property Measurement

In addition to a large initial transient time, the probe thermal properties (resistivity, heat capacity) can affect the measured soil thermal resistivity. For instance, the 25 mm diameter probes, when calibrated against laboratory probes gave 20% higher values for the thermal resistivity. Thus a 20% correction had to be applied to field data.

For in situ tests the maximum test time is no longer of concern since there are no radial boundaries to limit test time. Thus it is possible to run a thermal stability test (Boggs and others, 1980). This involves a standard low power thermal resistivity test, immediately followed by another run of the same duration, only with ten times the power (Fig. 9). In a thermally unstable soil the high heat run will induce significant moisture migration away from the probe thus increasing the thermal resistivity. In a thermally stable backfill soil, the thermal resistivity values from the low and high power runs will be similar.

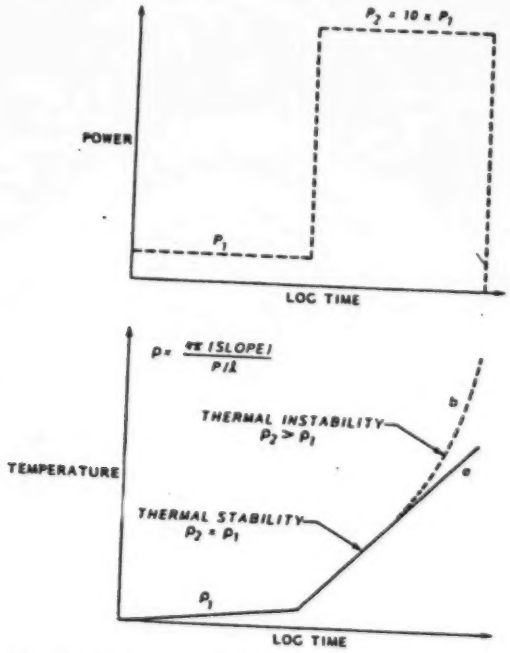


Fig. 9 Two-power thermal resistivity measuring technique for the determination of thermal stability

The field probe must be inserted carefully to assure good probe to soil thermal contact and minimal disturbance of the natural soil. In sufficiently soft soils (ie soft clays), a 1 m long 10 mm diameter probe can be inserted by hand. In general, a guide jig and pre-drilled pilot hole are necessary. The guide must be securely pegged into the ground so as not to move and distort the hole. Even when pushing a probe, a suitable guide is desirable to keep the probe in line and minimize hole distortion caused by side-to-side movement of the probe.

In stiff soils a probe cannot be pushed and a pilot hole must be drilled. In this case a guide is used to keep the long-shafted drill in line (simply a hand held power drill). The drill should only be advanced the length of the bit before the flutes are cleaned so that the drill is cutting and removing material rather than

pushing and displacing the soil. Drill bits should be no larger than the probe diameter and preferably slightly undersized. The smallest diameter pilot hole should be drilled which permits the probe to be inserted, so that the good probe-soil contact is achieved. In soil with coarse angular particles, the probe may catch and cannot be inserted at all. In this case, the pilot hole must be drilled to the exact size. The probe should never be hammered since at worst it may be damaged and at best may disturb the resident material and result in a distorted hole with poor probe-soil contact. To prevent bending the probe, a hand-held gripper can be used to push the probe from about 150 mm above the soil surface. If necessary, a hydraulic jack may be required (Cameron and Brookes, 1960).

The selection of drill size and the insertion technique for different soil conditions comes with practical experience. In homogeneous fine grained soils or those containing only fine gravel fractions the above techniques are successful. In soils containing coarse gravel particles or cobbles (glacial tills) that cannot be dislodged by drilling, probe insertion can turn out to be a trial and error procedure. Several pilot holes may be necessary before one goes through without striking an obstruction. In cases where a probe is only partially inserted, a valid run may be carried out for the embedded thermocouples, but care must be taken not to overheat the protruding part of the probe.

One metre flights of probe can, in general, be inserted with minimal effort and distortion of the hole, resulting in good probe-soil thermal contact. Longer lengths usually result in considerably more disturbance of the hole and increased difficulty with hand pushing methods, due to increased soil friction on the sides of the probe and crookedness inherent to long probes. Thus the use of one-meter probes is convenient except where measurements are required at greater depths. For great depths, a longer probe with an active length of only 1 m can be advanced in flights of 1 m. Field experience indicates that a 10 mm diameter probe is the smallest size that offers sufficient rigidity for the rigours of field use. A smaller diameter, such as 6 mm, is too flexible and causes hole distortions during predrilling or pushing, resulting in substantial contact resistance. The 6 mm probe may be used to advantage in cases, such as tills, where a thinner probe may slip in more easily between the larger stones or in cohesive clays where side friction makes the pushing of the larger diameter probes difficult.

CONCLUSIONS

The transient thermal probe is a relatively quick , versatile method of measuring the soil thermal properties. Valid results can be obtained if the test conditions approximate, as closely as possible, the constant power, line source of heat in an infinite medium theory. The probe to soil contact resistance, probe heat capacity, and the sample boundary conditions, if not accounted for, can significantly affect the test results.

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DISCUSSIONS

W.Z. Black, Georgia Institute of Technology *In Figure 5 you identify "critical moisture" contents for several soils, implying that soil will be thermally stable when its moisture content is above the "critical" value. The research effort at Georgia Tech and Georgia Power has identified the heat input per unit length as also being an important parameter influencing the thermal stability. We are afraid that many who are not skilled in making stability measurements will use your simplified stability model and will regard the moisture content of the soil as the only factor which needs to be considered.*

From our research work, for example, we have shown that Georgia clay can be unstable for moisture contents up to 20% which is well above the value that you have identified as the "critical moisture" content. This illustrates the danger of using a single moisture content as an important stability parameter simply because it is located near the knee of the rho vs moisture curve.

Would you comment on how you can use the single value for critical moisture content when, in addition, the stability is also a function of the heat generated within the cable.

J.E. Steinmanis *In general, the thermal stability of a soil is a function of the thermohydraulic properties of the soil, which depend on moisture, time, and heat input. Soils suitable as thermal backfills do exhibit a stable thermal resistivity above a "critical" moisture content, for any realistic power dissipation. The thermal resistivity versus moisture content curve (which can be fairly easily determined by stage-drying, two-power tests on laboratory samples (Boggs and others, 1980)) for these soils has a sharp knee and therefore the "critical" moisture can be clearly defined. In a cable installation, good thermal soil is placed near the cable, therefore the simple concept of a "critical" moisture can be used as the indication of the thermal stability of the system.*

For thermally unsuitable soils, such as Georgia clay, the thermal resistivity increases fairly steadily with decreasing moisture and the thermal stability depends on the heat flux. In this case more complex testing, that will consider both the initial moisture content and power dissipation, would have to be done to characterize the thermal stability of the soil. But in general this is not necessary since the native soil outside the backfill experiences such a low heat flux that thermal drying and instability will not occur.

In Figure 5 a relative "critical" moisture content is indicated for the poor thermal soils only for the purpose of comparison with the good thermal soils. A low "critical" moisture and a sharp bend in the curve indicates a good thermal backfill.